For Presentation at 41st AIAA Structures, Structural Dynamics, and Materials Conference

Transient Load Analysis and Testing of QuikSCAT Spacecraft

Michael Vujcich
Ball Aerospace & Technologies Corporation
Boulder, CO
Mvujcich@ball.com

Chin-Po Kuo
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA
Chin-po.kuo@jpl.nasa.gov

ABSTRACT

The QuikSCAT satellite was the first contract awarded under the NASA Rapid Spacecraft Acquisition (RSA) program. An aggressive schedule (one year from contract award to launch) required a modified approach to the loads analysis and environmental testing program from that of a typical spacecraft program. A successful approach used to develop spacecraft design loads and perform spacecraft environmental testing within the NASA "Faster, Better, Cheaper" environment is discussed along with problems encountered involving higher than anticipated loads late in the program.

INTRODUCTION

The NASA Quick Scatterometer (QuikSCAT) spacecraft contract was awarded in November 1997 with a scheduled launch in November 1998. The QuikSCAT program managed by NASA's Goddard Space Flight Center (GSFC) and Jet Propulsion Laboratory (JPL) consists of a the SeaWind microwave radar instrument that measures the near surface wind velocity over the oceans integrated on a Ball Aerospace RS2000 Commercial Spacecraft Bus. The Launch Vehicle is a Lockheed Martin Astronautics Titan II. The QuikSCAT mission is a replacement for the JPL NASA Scatterometer (NSCAT) which was lost when the ADEOS I spacecraft failed on 6/30/97.

A typical spacecraft development program will include multiple coupled loads analysis (CLA) cycles to determine spacecraft response loads to launch vehicle transient excitations. Typical cycles include; (1) a preliminary cycle with a simplified mathematical model and a model uncertainty factor (MVP), (2) a final cycle with a detailed mathematical model and lower model MUF, and (3) a verification cycle with a test verified model. Due to schedule constraints, a single CLA cycle was planned for the QuikSCAT program instead of the multiple cycles. As a means of risk reduction, a Dynamic Uncertainty Factor (DUF) of 1.25 was maintained throughout the program. The DUF differs from the MUF in that only the launch vehicle transient responses are subjected to the uncertainty factor; the steady state portion of the load is not.

Model verification is typically accomplished by a modal survey to identify the dynamic characteristics of the spacecraft. For the QuikSCAT program, a limited model verification was planned using the results of sine sweep vibration testing with the spacecraft mounted to a shaker with excitation along the thrust axis and along one lateral axis.

The strength of the spacecraft structure is typically verified by subjecting a dedicated test article to qualification level static load testing or the flight article to protoflight level static load testing. For the program, strength verification was accomplished by subjecting the flight article to a protoflight level quasi-static sine burst test with the spacecraft mounted to shaker along the thrust axis and one lateral axis. Some components which were not fully loaded by the sine burst test were validated by a stress analysis using "no test" factors of safety of 2.0 against yield and 2.5 against ultimate failure.

Acoustic testing is typically performed with the spacecraft in a reverberant chamber. An innovative approach to acoustically test the spacecraft in-situ while installed on the shaker table was used. This approach is fully described in Reference 1.

DESIGN ENVIRONMENTS

The maximum predicted quasi-static limit load factors (intended as a conservative envelope of flight events) were specified as +11.0 G (Stage II Shutdown) in the thrust direction and +/- 2.5 G (Stage I Fuel Depletion) in the lateral direction per the Titan II user's guide.

There is no structure-borne sinusoidal or random vibration environment specified for the Titan II. A minimum workmanship base input random vibration spectrum was developed by JPL as shown in Table 1.

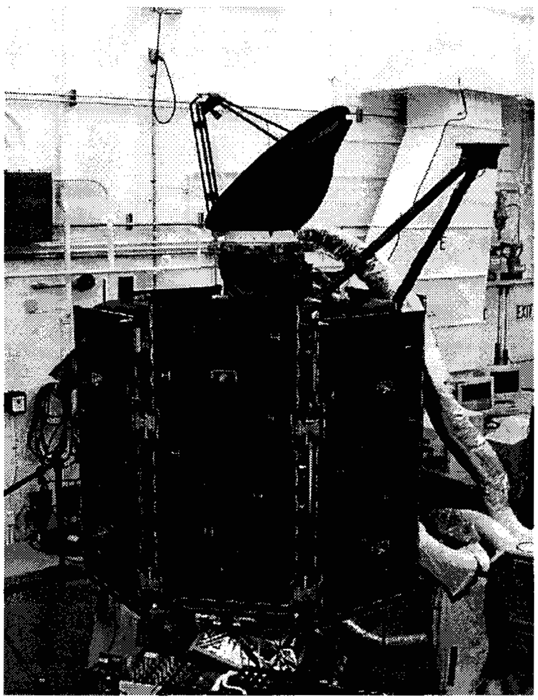

Figure 1 - QuikSCAT Spacecraft

Table 1 - Protoflight Random Vibration Environment

Frequency (Hz)	Power Spectral Density (G^2/Hz)
10	0.01
10 - 20	+ 3.0 dB / octave
20 - 200	0.02
200 - 500	-3.0 dB / octave
500	0.008
Overall	2.7 Grms

The acoustic design environment consists of the predicted environment within the Titan II payload fairing and was modified by JPL for minimum workmanship levels. The design and protoflight acoustic environments are shown in Table 2.

Table 2 - Acoustic Environment

Third Octave Band Center Frequency Hz	Design Level dB (rel .0002 Pa)	Protoflight Test Level dB (rel .0002 Pa)
31.5	111.6	114.6
40	113.8	116.8
50	114.8	117.8
63	116.2	119.2
80	119.7	122.7
100	120.2	123.2
125	121.3	124.3
160	120.4	123.4
200	120	123
250	120.8	123.8
315	121.5	124.5
400	121.3	124.3
500	121.3	124.3
630	121	124
800	118.8	121.8
1000	115.5	118.5
1250	115.8	118.8
1600	113.5	116.5
2000	111.5	114.5
2500	110	113
3150	108.5	111.5
4000	104.6	107.6
5000	102.7	105.7
6300	100.1	103.1
8000	96	99
10000	93.5	96.5
OASPL	131.8	134.8

PRELIMINARY DESIGN LOAD CALCULATION

Prior to the availability of CLA results, an analysis was performed to establish design loads for the QuikSCAT primary structure and components. The analysis considered the combined effects of launch vehicle acceleration (steady state and low frequency transient) structure borne random vibration, and acoustically induced vibration. The NASTRAN finite element model of the spacecraft is shown in Figure 2.

The net CG acceleration was separated into two cases specified in Table 3. Case 1 is an envelope of the liftoff and max airload cases. Acoustics and random vibration were added to this case. Case 2 is an envelope of Stage I and Stage II shutdown.

Transient response accelerations at various points on the spacecraft were estimated by applying a base drive acceleration to the model described above. The input acceleration was varied in order to maintain a net CG load of 2.5 G in each direction.

In the lateral axes, the input was varied between 1 and 14 Hz (1.4 times the 10 Hz critical frequency per the Titan II users guide). Along the thrust axis, the input was varied between 1 and 34 Hz (1.4 times the 24 Hz critical frequency per the Titan II users guide. This was done to attempt to develop a conservative design load for components along the length of the spacecraft (i.e. components higher up will have a higher lateral load).

Table 3 - Spacecraft Net CG Design Load Factors

Axial Acceleration (G's Limit)

Case	Steady State	Transient	Total
1	2.0	+/- 2.5	-0.5 to +4.5
2	8.5	+/- 2.5	6.0 to +11.0

Lateral Acceleration (G's Limit)

Case	Steady State	Transient	Total
1	0	+/- 2.5	+/- 2.5
2	0	+/- 2.5	+/- 2.5

Although not explicitly specified as a flight environment, the random vibration environment shown in Table 1 was used as a flight level structure borne random interface input at the launch vehicle/spacecraft interface.

A frequency response analysis was performed for a 1G base drive input acceleration along each axis. Modes up to 1200 Hz were retained in the solution and responses where calculated up to 500 Hz. A damping factor of 4% of critical was used in the response calculations.

A random response analysis was performed using the input from Table 1 as a base drive acceleration. The same analysis parameters from the frequency response analysis were used. The input was notched in order to provide a force-limited input such that the net CG load factor was limited to the input spectrum.

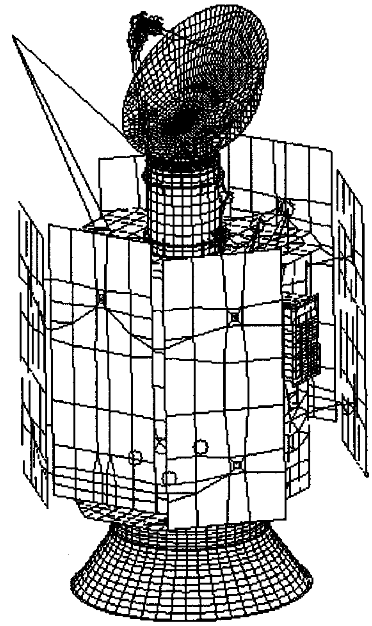

Figure 2 – Spacecraft NASTRAN Model

Acoustic responses were computed using a VAPEPS model developed by JPL. The curve shown in Figure 3 is an envelope of responses on the spacecraft panels and instrument interfaces.

The steady state acceleration, transient acceleration, acoustic, and structure-borne random vibration loads were combined using the procedure specified in Reference 2.

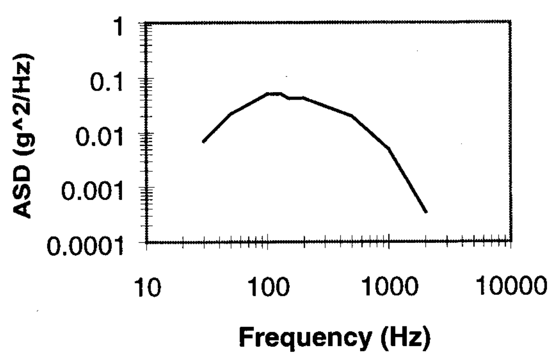

Figure 3 - Acoustic Response PSD

This method of combination as follows:

$$Ni = Si +/- [(Li)^2 + (Ri)^2]^{0.5}$$

where:

Ni = Combined load factor
Si = Steady state load factor
Li = Low frequency transient load factor
Ri = Random vibration load factor

Spacecraft bus component responses ranged from 3.3G to 27.4G in the lateral axes and from 11.0G to 18.8G along the thrust axis using this superposition approach.

Preliminary design load factors for the scatterometer and two other instrument boxes were based on a Mass Acceleration Curve (MAC) developed by JPL for the ADEOS II program.

INITIAL COUPLED LOADS RESULTS

A transient response analysis (coupled loads analysis) was performed by Lockheed Martin Astronautics to compute design internal loads in the spacecraft primary structure. The Stage I Fuel Depletion event was determined to be critical resulting in interface loads significantly in excess of the spacecraft structural capability. The predicted base shear was 9690 lb. limit and the predicted statistical maximum base bending moment was 660612 in-lb. limit. The statistical maximum base bending moment (3.26 sigma) was reduced to 534758 in-lb. limit by performing an oxidizer depletion shutdown as opposed to fuel depletion. The CLA was performed for a set of 14 forcing functions based on nozzle pressure measurements from previous flight data.

Initial investigation revealed that the high lateral loads were due to a differential thrust generated during Stage I depletion. Upon fuel/oxidizer depletion, a differential thrust shown in Figure 4 results as "sputtering" occurs in one of the nozzles. The differential thrust causes a bending moment applied to the launch vehicle and a subsequent high lateral acceleration on the payload.

Furthermore, the QuikSCAT spacecraft was determined to be the lightest/stiffest payload flown to date on Titan II and that there was a significant coupling of the spacecraft primary bending modes with the booster modes which had not been experienced previously. The QuikSCAT spacecraft has a weight of 2100 lb., and a first lateral bending frequency of 20 Hz compared with previous Titan II payloads in the 4000 lb. range with lateral bending frequencies around 10 Hz. The coupled spacecraft/booster bending frequency was predicted to be 13.3 Hz, directly in line with the peak response shown in Figure 4.

Three parallel approaches were explored to solve the loads issue; an isolation system to reduce the coupling between the spacecraft and the launch vehicle, a different statistical treatment of the loads, and flight at the higher loads with reduced margins.

A conceptual design of a low cost series of isolators was developed by CSA engineering. The isolation system was designed to lower the first lateral bending frequency of the spacecraft to 10 Hz while maintaining an axial frequency greater than 24 Hz. The isolation system also incorporated constrained-layer damping technology. An abbreviated coupled loads analysis demonstrated that the loads could be lowered to within the original design levels. Although the design of an isolation system was successful, it was not pursued by the program.

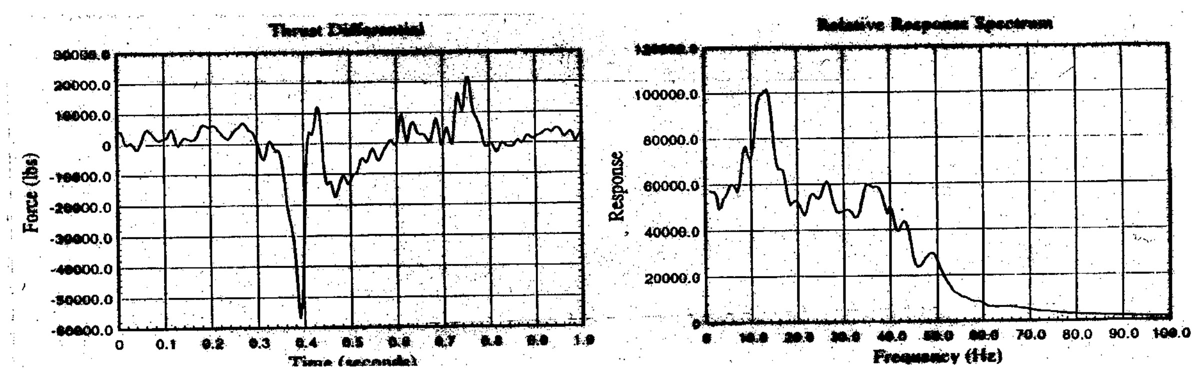

Figure 4 – Stage 1 Oxidizer Depletion Thrust Differential and Relative Response Spectrum

An Alternate statistical treatment of the transient flight events was proposed as a second solution. This approach was generally not embraced by the community due to its reduced conservatism.

The third approach to fly at higher loads with reduced margins was demonstrated to be feasible through refined stress analysis of the spacecraft separation system and launch vehicle adapter and interface structure and a reduction of the protoflight test factor from 1.25 to 1.10.

The program chose to accept the higher level of risk and fly at the higher loads.

RISK REDUCTION ACTIVITIES

An additional frequency sensitivity study was performed by JPL as a means of additional risk reduction.

An approach was proposed to assess the upper bound of transient loads, which resulted from the variation of major frequencies of the spacecraft. The Substitution Coupled Transient Analysis (Ref. 3) developed by JPL was applied. This method is a very cost effective technique to estimate transient load variations due to the uncertainty of spacecraft frequencies. The method takes a given coupled transient analysis of the existing launch vehicle/spacecraft system to determine the loads while the spacecraft has some modifications and the rest of system are intact. The method is an exact analysis in both frequency domain and time domain of the dynamic coupling analysis between the launch vehicle and the spacecraft. It eliminates a costly and time consuming restart of coupled load analysis.

As mentioned, the major frequency of the finite element model of the spacecraft was coupled with launch vehicle and excitation force. A tuning technique was used by assuming that the frequencies of the launch vehicle were intact and the frequencies of the spacecraft were turned up and down but the mode shapes were remained same. This change means that the properties of the spacecraft were modified proportionally throughout the entire model. The range of variations is from 30% to 170% of first frequency of the model. The variation of overturning moment (actual predicted - lower than the statistical maximum mentioned previously) at the major axis is shown in Figure 5.

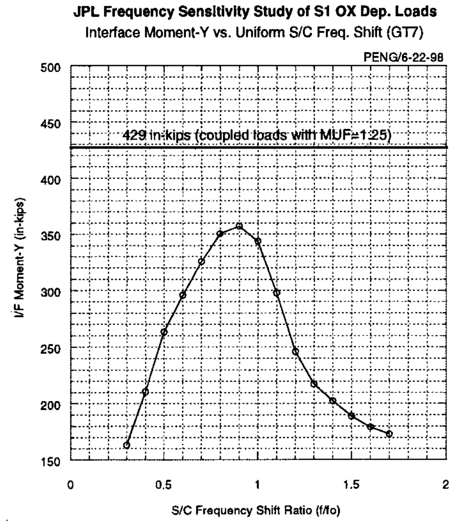

Figure 5 - Variation of Base Bending Moment vs Spacecraft Frequency

Figure 5 indicates that the absolute maximum base bending moment at the spacecraft/launch vehicle interface cannot be reduced unless the first frequency is reduced more than 24%. Even a 40% reduction in frequency results in only a 20% reduction in the bending moment. On the other hand, the moment is bounded by only 5% excess. The potential extreme 5% over the design limit is within tolerance of engineering analysis methods, material properties, and modeling techniques. It seems reasonable to review the conservation in the design and analysis method in junction with reduction of margin of safety.

Due to the reduction of the protoflight test factor from 1.25 to 1.10, additional risk reduction was achieved by the use of force limited loads and vibration testing. Eight piezo-resistive force gages were incorporated into the loads/vibration test fixture to directly measure the base interface axial force, shears, and base bending moments during the testing discussed below.

ENVIRONMENTAL TEST PROGRAM

A complete description of the test setup and results is found in Reference 4.

A quasi-static sine burst test was performed along 2 axes, one lateral and one longitudinal, to demonstrate the structural integrity of the QuikSCAT spacecraft under maximum loading conditions.

The lateral axis test consisted of a sinusoidal input at 12 Hz with 5 cycles to ramp up to full level, 6 cycles at full level, and 5 cycles to ramp down from full level. The peak bending moment at the spacecraft/launch vehicle interface was 587675 in-lb., which represents 99.9 % of the required protoflight base bending moment of 588233 in-lb. (measured at the plane of the force gauges).

After successful completion of the sine-burst quasi-static loads testing, the spacecraft was subjected to a force-limited random vibration test for workmanship verification. The input acceleration specification for both the lateral and vertical random vibration tests consisted of a flat input acceleration spectrum of 0.2 G^2/Hz from 20 to 200 Hz with a 3 dB/octave roll-off from 20 to 10 Hz and from 200 to 500 Hz. The lateral axis test involved limiting the overturning moment, in-axis shear force, and two critical responses. The axial test involved limiting the axial force and the nadir deck axial response. In addition, the axial test was stopped after a –3 dB run, because a number of components were at their flight-limit loads.

Low level (0.1 G input) sine-sweep tests were conducted at the beginning and the end of each axis of testing. Since there was no separate modal test of the QuikSCAT spacecraft, the sine sweep tests provide data to determine the fixed-base natural frequencies and limited primary mode shapes of the spacecraft in order to validate the analytical model used to predict the spacecraft loads.

The initial 0.1G input sine–sweep tests preformed at the beginning of the lateral and vertical axis tests are shown in Figures 6 and 7, respectively. There was no significant change in the sine-sweep signatures before and after loads testing which indicates that the structural integrity of the spacecraft was not compromised during testing.

MODEL CORRELATION

A fairly extensive pre-test analysis was performed for the test environment and correlation with measured test results was generally very good. Results from an initial 0.1G sine sweep for the thrust axis and one lateral axis are shown in Figures 6 and 7. The data in these figures are from the force gauges located at the spacecraft/launch vehicle interface.

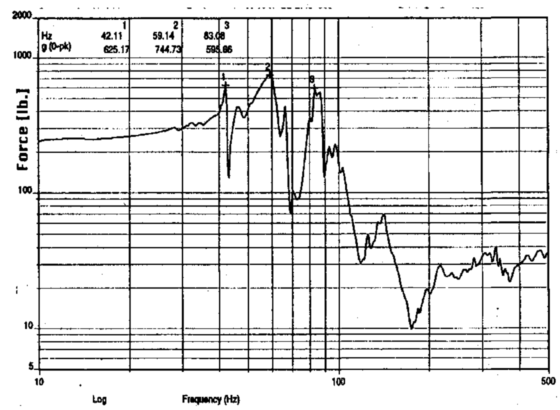

Figure 6 - Thrust Axis Initial Sine Sweep Data

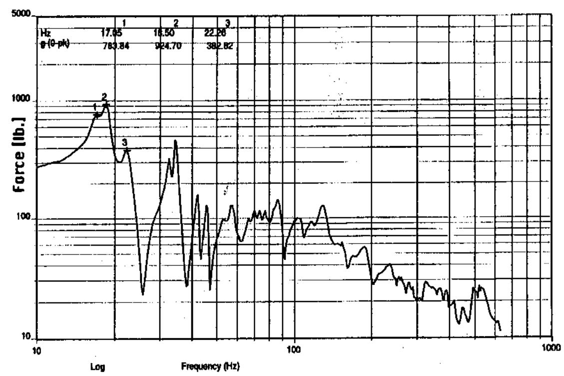

Figure 7 - Lateral Axis Initial Sine Sweep Data

The pre-test prediction of the first lateral bending frequency was 17.8 Hz (for the test configuration mounted on the vibration fixture and shaker. Figure 7 shows a double peak at 17.05 Hz and 18.50 Hz. After testing, the model was updated to better match the test data. Changes included a modification to the separation system clamp band and a softening of the spacecraft upper deck.

The test fixture was removed from the model and the updated spacecraft fixed base modal frequencies below 50 Hz are shown in Table 4.

Table 4 - Updated Prediction for Fixed Base Frequencies

Updated Model Fixed Base Spacecraft (No Test Fixture) **Hz**	Mode Description
19.5	Spacecraft Lateral Bending (CG +/- SV X)
22.8	Spacecraft Lateral Bending (CG +/- SV Y)
29.7	RF Antenna Mast Z Translation
32.9	Propulsion Tank CG +/-X With SAS Lateral Translation +/-X
34.8	SAS Lateral Translation +/-X
35.9	Propulsion Tank CG +/-Y With SAS Lateral Translation +/-Y
40.8	SAS Lateral Translation +/-Y
43.3	Mast Tube Bending
43.6	Mid Deck Bounce
47.9	SAS Bounce on Nadir Deck

CONCLUSION

The QuikSCAT structural loads analysis and environmental test program is an example of a successfully streamlined effort in a NASA "faster, better, cheaper" environment. Success was achieved through a high degree of concurrent engineering and cooperation between the customer, spacecraft contractor, and launch vehicle contractor.

ACKNOWLEDGEMENTS

The work described in this paper was carried out by the Jet Propulsion Laboratory (JPL), California Institute of Technology under a contract with the National Aeronautics and Space Administration (NASA) and by Ball Aerospace and Technologies Corporation (BATC) under a contract with NASA. The authors would like to thank their colleagues and the program offices at JPL, GSFC, BATC, Lockheed Martin Astronautics (LMA) and the Aerospace Corporation for their contributions to the success of this effort. Particular thanks are extended to Alan Posey (GSFC), Terry Scharton (JPL), Chia-Yen Peng (JPL), John Garba (JPL), Steve Shum (LMA), Phil VanLaw (LMA), and Greg Hiestand (LMA).

REFERENCES

1. T. Scharton, D. Anthony, and A. Leccese, "Direct Acoustic Test of QuikSCAT Spacecraft", Sixth International Congress on Sound and Vibration, Denmark, Copenhagen, July, 1999.

2. "General Environmental Verification Specification for STS and ELV Payloads, Subsystems, and Components", GEVF-SE, Revision A, GFAC, NASA, June 1996.

3. M Trubert & L. Peretti "A cost-effective component modes analysis doe Shuttle payloads using a combination of frequency domain and time domain approaches" Paper-0733-CP-85-0733, 26th AIAA SDM Conference, Orlando Fl, April 15-17,1985

4. T. Scharton and M. Vujcich, "Combined Loads, Vibration, and Modal Testing of the QuikSCAT Spacecraft", Journal of the Institute of Environmental Sciences and Technology, Volume 42, Number 5, September/October, 1999.